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Lunar Simulants, Analogues, and Standards: Needs and Realities for Mission Technologies Development

Laurent Sibille

Team ESC-QNA

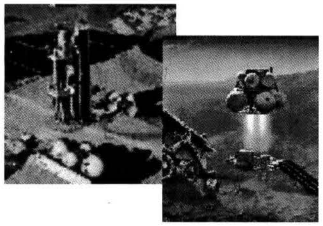
Surface Systems Group

NASA Kennedy Space Center, FL

Why does NASA need requirements on dirt?

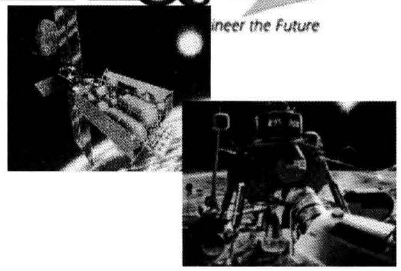
- The needs of multiple disciplines and projects
  - Exploration surface vehicles
  - Resource characterization equipment
  - Regolith processing equipment
- The needs of the exploration program
  - Need to validate approaches and make comparisons
  - Need to recommend test standards

In-Situ Resource Utilization Can Provide Significant Benefits to Mission Architectures



Mass Reduction

- >7.5:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit
- Reduces Lunar mission launch mass by 27 to 88% depending on reusability and propellant depot options



Cost Reduction

- Allows reuse of transportation assets
- Reduces number and size of Earth launch vehicles
- Minimizes DDT&E & operation costs thru use of common technologies

Space Resource Utilization

Risk Reduction & Flexibility

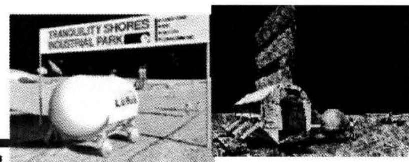
- Provides 'safe haven' capabilities for aborts and delayed cargo resupply
- Can reduce number of launches and mission operations
- Radiation and landing/ascent plume shielding
- Increases flexibility and options for contingency and failure recovery operations
- Reduces dependence on Earth

Enables Space Commercialization

- Provides infrastructure, technologies, and market to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

Expands Human Presence

- Increases Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.
- Substitutes propellant & consumable mass for new science or infrastructure cargo

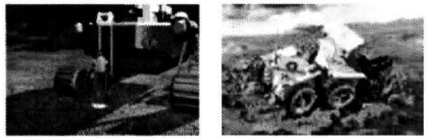


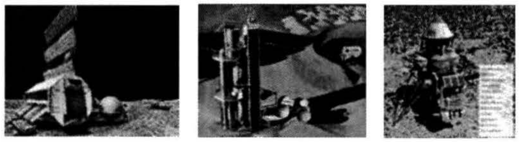
What is In-Situ Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Five Major Areas of ISRU

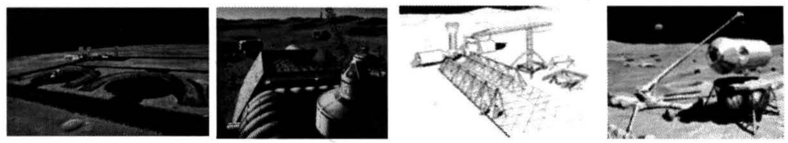
- **Resource Characterization and Mapping**
  Physical, mineral/chemical, and volatile/water





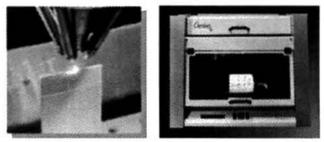
- **Mission Consumable Production**
  Propellants, life support gases, fuel cell reactants, etc.

- **Civil Engineering & Surface Construction**
  Radiation shields, landing pads, roads, habitats, etc.



- **In-Situ Energy Generation, Storage & Transfer**
  Solar, electrical, thermal, chemical

- **In-Situ Manufacturing & Repair**
  Spare parts, wires, trusses, integrated structures, etc.



- **'ISRU' is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.

NASA Development of Lunar and Mars ISRU Technologies & Systems: 2005-2012

Resource Characterization & Mapping

- Lunar polar ice/volatile characterization
  - RESOLVE

In-Situ Energy Generation, Storage & Transfer

- Solar Concentrators
- Heat Pipes

Civil Engineering & Surface Construction

- Lunar Regolith Excavation
- Lunar Regolith and Mars Soil Transfer
- Lunar Regolith Size Sorting & Beneficiation
- Lunar Regolith Simulant Production
- Surface Preparation

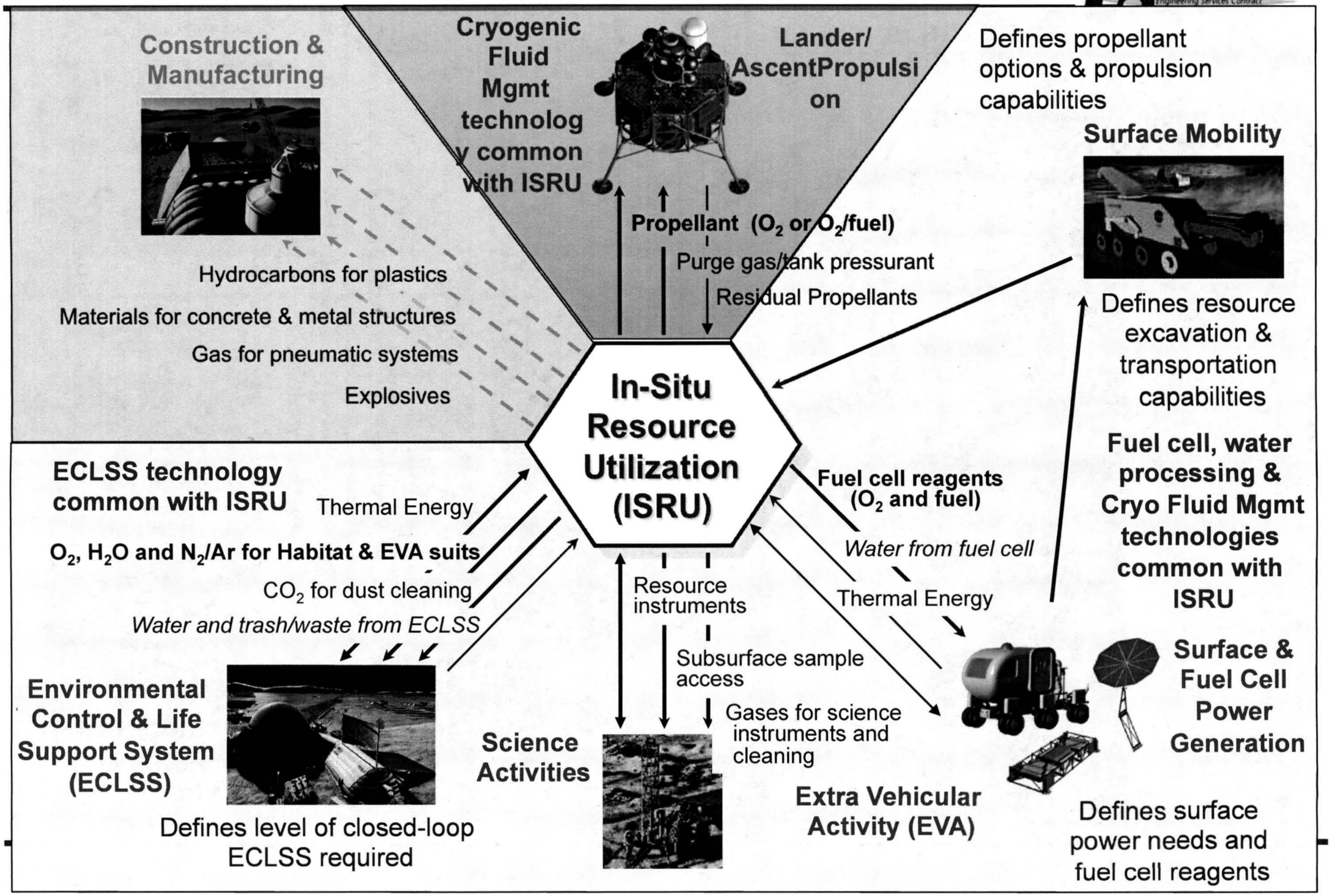
Mission Consumable Production

- Oxygen Extraction from Regolith
  - Hydrogen Reduction
  - Carbothermal Reduction
  - Molten Oxide Electrolysis
  - Ionic Liquids
- Oxygen and Fuel from Mars Atmosphere
  - Carbon Dioxide Capture
  - Mars Soil Drying
  - Microchannel Reactors
- Water and Fuel from Trash
  - Steam Reforming
  - Combustion/Pyrolysis
- Water Processing
  - Water Electrolysis
  - Water Cleanup

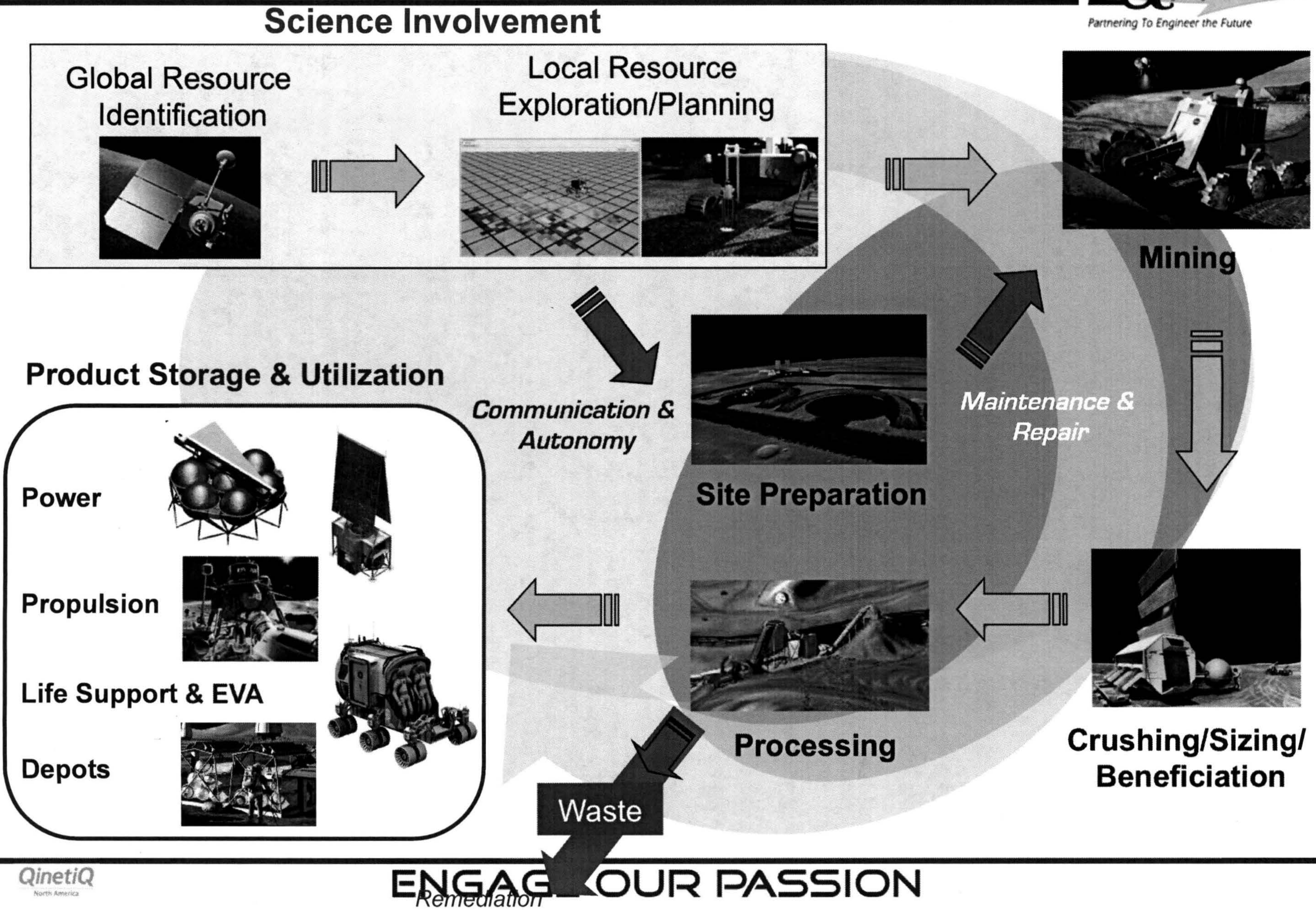
Main Areas of ISRU and Applicability to Surface Systems

	EVA	Life Support	Power	Propulsion	Manufact-uring	Habitats	Science
Resource Characterization & Mapping							
Geotechnical & mineral characterization	X				X	X	X
Water/volatile characterization in regolith/ soil	X	X	X	X			X
Consumable Production							
Oxygen	X	X	X	X		X	
Hydrogen		X	X	X			
Methane			X	X			
Water	X	X				X	
Nitrogen		X				X	X
Cleaning & Inert Gases (CO_2, He)	X						X
Plant growth media & feedstock		X					
Manufacturing feedstock					X		
Civil Engineering & Construction							
Pads/berms/roads			X			X	X
Radiation shielding		X	X			X	X
Structures/Habs						X	X
Energy Production & Storage							
Thermal energy storage & gen			X			X	
Electrical energy gen			X				
Manufacturing & Reuse							
Part fabrication					X		
Hardware scavenging & recycling					X		

ISRU Strongly Influences Element Designs and Architecture Choices



Space ‘Mining’ Cycle & Integration with Surface/ Transportation Elements



ISRU & Surface System Development & Integration Challenges

Life:

- Hardware and systems must operate for months and years and not just days in the harsh lunar vacuum, radiation, thermal, and dust environment

Schedule:

- Nations/space agencies must be allowed freedom to pursue areas of interest with delivery dates that are consistent with their budgets

Interoperability:

- Hardware and systems from multiple countries must be compatible with each other to achieve desired capabilities and operations

System/Element Integration:

- Critical systems, such as power, propulsion, thermal, and life support for each major lunar surface element are often designed and optimized based on their own requirements instead of from a more integrated element/vehicle perspective or surface architecture perspective.

Importance of Analog Field Testing to Prepare for Human Exploration Beyond Low Earth Orbit

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Analog Field Tests Validate Key Integrated Architecture Requirements and Concepts

Technology Development
(Energy Storage, Robotics, Human Factors, etc.)

Architecture Element Concept
(Rover, Habitat, Robotics, Power, ISRU, etc.)

Surface Operation/Integration Concepts
(Outpost Maintenance, Exploration, etc.)

Science Concepts
(Site Survey's, Geological Sampling/Curation, etc.)

Crew Training
(Outpost Maintenance, Science, Exploration, etc.)

Outreach & Participatory Exploration
(Web 2.0, Virtual Reality, Simulations, etc.)

Analog field tests emphasize collaboration between ESMD, SMD, Commercials, OGAs & IPs

Exploration Mission Analog Types

Mission Focused Analog

- Focus on performing relevant mission scenarios
  - Mission relevant hardware not as important
- Stress timeline and operations
- Examine remote operations and procedures
- Examine system/capability influence on mission

Hardware Focused Analog

- Focus on mission relevant hardware and scale
- Stress hardware (get out of laboratory)
- Examine how environment impacts hardware design and operation
- Examine integration and interaction of hardware and systems

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Desert RATS
NEEMO
Pavilion Lake

3rd Hawaii ISRU – Surface Ops

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1st & 2nd Hawaii ISRU – Surface Ops

ISRU-Surface Operations Analog Test Focus
Hardware Focus

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Space Mining Cycle Module & Operation Objectives

Demonstrate mobile resource characterization (physical, mineral, and volatile) capabilities for lunar polar missions

- Link science operations and instrumentation with site characterization & resource prospecting/mapping needs

Demonstrate technologies and end-to-end system operations for mission critical consumable production on Moon, Mars, & NEO's (oxygen, water, fuel)

Demonstrate civil engineering and site preparation capabilities that might be required for future human missions (landing pads, roads, protection, etc.)

Surface Element /Transportation Module & Operations Objectives

Link Power, Propulsion, Life Support, ISRU, and Cryogenic Fluid Management technology, system, and module development efforts within NASA (ETDD, OCT, SBIR, IR&D) and with industry and external partners

Develop interfaces and standards for fluids/electrical/data

Demonstrate performance and operations of modules for all surface and transportation system elements.

Demonstrate evolutionary growth of capabilities through technology and module upgrades when available

What are the needs of the technology projects?

- Needs of the surface vehicles
  - Physical and geotechnical
- Needs of the regolith handling hardware
  - Physical and mineralogical
- Needs of the regolith processing hardware
  - Mineralogical and chemical
  - But also…physical as well (example of RESOLVE devpt – fluidization, interfaces with the crusher)

Designing requirements for ‘special dirt’ … what approach to choose?

Start with our knowledge of the Moon

- Apollo and Luna samples data
- Apollo surface observations and measurements

Identify what features are mineralogical in nature and those that are due to formation processes specific to the Moon

- Mineralogical features can be reproduced with some exceptions
- Formation processes are more challenging or even impossible to reproduce

Approach to requirements

The needs of the various technology development areas overlap

- Physical features like grain size, shape and bulk density are important to all
- Modal composition is critical to guarantee that simulants can be used by many users

Some needs are over riding

- Chemical compositions can be controlled by proper choice of terrestrial minerals but source locations are very important
- Choosing the mineralogy of the simulant becomes a top priority to simulate the right geotechnical properties and control the chemical composition for chemical processing

A focus on lunar highlands is a good place to start:

- The highlands represent 75% of the lunar surface
- The regolith possesses a remarkable physical uniformity throughout the lunar surface
- What mineralogy to choose?
  - Fewer returned samples represent the Highlands
  - Norite is a dominant component
- Ranking of needs is important to identify the economics of simulant materials and their level of fidelity (FoM)

Lunar Highlands Regolith Simulants

The mineralogical variety of the Highlands is not tightly bound

- Choices must be made to avoid trying to duplicate every sample known
- Representation of several critical minerals and lithic components is needed to control both the physical properties and the chemical composition
- Current approach by NASA is to identify simulant materials from different sources and provide an evaluation tool based on figures of merit (FoM)

Major requirements

- Modal composition
- Grain size and distribution
- Grain shape and distribution
- Bulk density

Environmental requirements

- Mixing procedures
- Compaction procedures
- Storage protocols

Summation

Integration of In-Situ Resource Utilization (ISRU) capabilities into missions presents both challenges as well as benefits for future missions to the Moon and Mars.

- However, since ISRU systems and capabilities have not flown, mission planners have been hesitant to include ISRU capabilities in mission critical roles, thereby significantly reducing the benefits that ISRU can provide in mission mass and cost reductions.

For ISRU systems to provide products and services to 'customers' such as life support, propulsion, and power systems, close development of requirements, hardware, and operations between ISRU and these systems are required.

To address these development and incorporation challenges, NASA and CSA initiated a series of analog field test demonstrations at sites in Hawaii.

- Two tests completed in November of 2008 and February of 2010 have demonstrate all the critical steps in operating ISRU systems on the lunar surface at relevant mission scales as well as integration with power and propulsion systems.
- The third field test planned for July 2012 will demonstrate that a mission to the lunar poles to locate and characterize ice and other volatiles is possible in a highly integrated mission with multiple space agencies.

➢ **These analog field tests have shown that not only are ISRU systems feasible at relevant mission scales, that they can be successfully integrated into mission architectures.**

Requirements on a few main properties of the regolith can be defined to drive simulant development

Production of the resulting simulants will be economically feasible while maintaining quality control

We must adopt a concept that enables quick response to changing knowledge and implementation of that knowledge between simulant batches.

Taxonomy of Lunar Simulant Materials

Current lunar simulant materials (U.S.)

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Simulant	Info	Type	Contact Info
United States:			
ALS	Arizona Lunar Simulant *Desai et al., 1993*	Low-Ti Mare (geotechnical)	
BP-1	KSC / Arizona Black Point quarry waste (Basalt) ; using for large excavation exercises with BLADE *Rahmatian & Metzger, in press*	Low-Ti mare (geotechnical)	Rob Mueller/KSC
CSM-CL	Colorado School of Mines – Colorado Lava *Unpublished*	geotechnical	
GCA-1	Goddard Space Center *Taylor et al., 2008*	Low-Ti mare (geotechnical)	
GRC-1 & -3	Glenn Research Center (Sand, clay mixture used in SLOPE Facility for mobility/excavation) *Oravec et al., in press*	Geotechnical: standard vehicle mobility lunar simulant	Allen Wilkinson/GRC
GSC-1	Goddard "Simulant"; material from local site that is being used for drilling tests		Peter Chen/GSFC
JSC-1*	Johnson Space Center *McKay et al., 1994*	Low-Ti mare (general use)	no longer available
JSC-1A , -1AF, -1AC	Orbitec created under a NASA contract .	Low-Ti mare (general use) (JSC-1A was produced from the same source material after a gap of some years when JSC-1 ran out)	http://orbitec.com/store/simulant.html
MKS-1	*Carpenter, 2005*	Low-Ti mare (intended use unknown)	
MLS-1*	Minnesota Lunar Simulant *Weiblen et al., 1990*	High-Ilmenite mare (general use)	no longer available (created in the 1980s)
MLS-1P*	*Weiblen et al., 1990*	High-Ti mare (experimental, not produced in bulk although small quanitites were distributed)	
MLS-2*	*Tucker et al., 1992*	Highlands (general use)	
NU-LHT - 1M, -2M, -1D, -2C	NASA/USGS Highland Type Simulant (Chemical/Mineralogical & Physical Properties) *Stoeser et al., 2009*	Highlands (general use)	Carole McLemore 256-544-2314 Carole.A.McLemore@nasa.gov http://isru.msfc.nasa.gov
Others			

Current lunar simulant materials (International)

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International:			
CAS-1	China (Chinese Academy of Sciences) a basaltic simulant made to represent Apollo 14 *Zheng et al., 2008*	Low-Ti mare (general use)	
CLRS-1	Chinese Lunar Regolith Simulant *Chinese Academy of Sciences, 2009*	Low-Ti mare (general use?)	
CLRS-2	*Chinese Academy of Sciences, 2009*	High-Ti mare (general use?)	
CUG-1	China *He et al., 2010*	Low-Ti mare (geotechnical)	presentation at LPSC 2010 conference
NAO-1	NAO-1, National Astronomical Observatories, Chinese Academy of Sciences *Li et al., 2009*	Highlands (general use)	
TJ-1 , TJ-2	China (Tongji University) ; a basaltic ash feedstock with olivine and glass *Jiang et al., in press*	Low-Ti mare (geotechnical)	presentation at Earth & Space 2010: Jiang M.J., Liqing Li, Chuang Wang, He Zhang, A New Lunar Soil Simulant in China, in press, Earth&Space, 2010 the 12th Biennial International Conference on Engineering,Science,Construction and Operations in Challenging Environments.
CHENOBI	Canada (Physical & Chemical properties simulant)	Highlands (geotechnical)	http://www.evcltd.com/index_005.htm
OB-1	Canada Olivine-Bytownite *Battler & Spray, 2009*	Highlands (general use geotechnical)	Jim Richard PH: 705-521-8324 x205 / jrichard@norcat.org http://www.norcat.org/innovation-regolith.aspx
FJS-1 (type 1) FJS-1 (type 2) FJS-1 (type 3)	Fuji Japanese Simulant *Kanamori et al., 1998*	Low-Ti mare Low-Ti mare High-Ti mare (general use)	http://www.shimz.co.jp/english/index.html
Oshima base simulant	*Sueyoshi et al., 2008*	High-Ti mare (general use)	
Kohyama base simulant	*Sueyoshi et al., 2008*	Intermediate between highlands and mare (general use)	
KOHLS-1	Korea Koh Lunar Simulant *Jiang et al. 2010*	Low-Ti mare (geotechnical)	presentation at Earth & Space 2010: Experimental Study of Waterless Concrete for Lunar Construction by Sung Won Koh, Jaemin Yoo, Leonhard Bernold, and Tai Sik Lee, Hanyang University, Korea.
Others - This may not be a complete listing.			

Classification of lunar simulants

Simulant materials can be classified by the type of regolith they simulate

- Mare materials
- Highland materials
- Special glass materials (e.g., pyroclastic)

Another classification arise by type of technology development

- Excavation, drilling and transport (BP-1, OB-1, Chenobi)
  - Simulants developed to reproduce physical properties mainly: shape, density, hardness, glass fraction, particle size distributions
  - These simulants are not necessarily high fidelity in mineralogy and chemistry
- Chemical processing (JSC1-A, NU-LHT-N1)
- Simulants developed to reproduce mineralogical and chemical compositions as well as some physical properties: major and minor components, inclusion of nanophase iron.
- These simulants tend to reflect higher fidelity

Technology Needs for lunar simulants

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- Examine remote operations and procedures
- Examine system/capability influence on mission
- Use of low fidelity simulant materials relevant to interfaces

Hardware Focused Analog

- Focus on mission relevant hardware and scale
- Stress hardware (get out of laboratory)
- Examine how environment impacts hardware design and operation
- Examine integration and interaction of hardware and systems
- Use of high fidelity simulant materials relevant to hardware functions